TEXAS A&M UNIVERSITY®

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LINE PROTECTION OPERATE TIME: SPEED VS. CIRCUIT BREAKER WEAR, POWER SYSTEM STABILITY AND PROTECTION SECURITY

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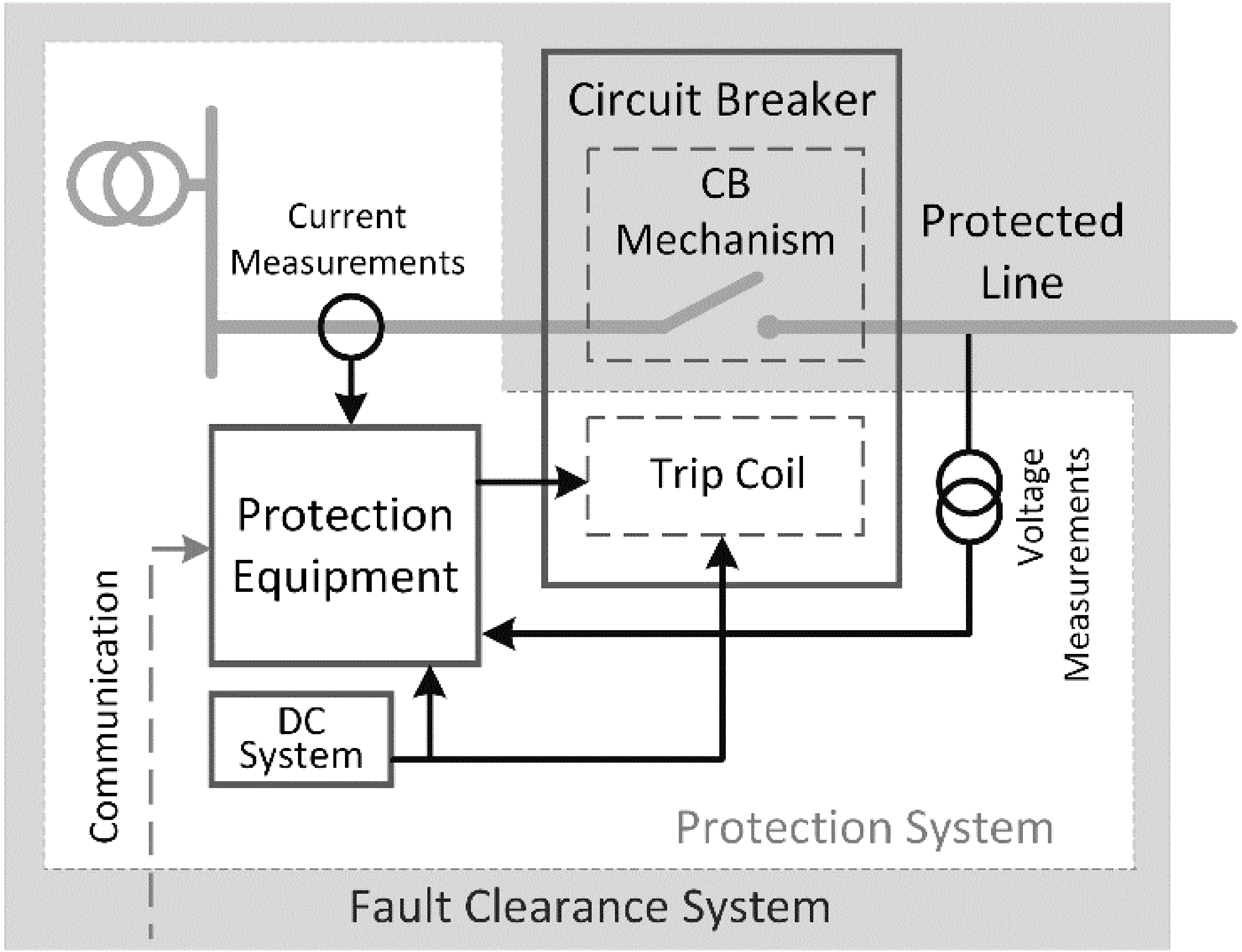
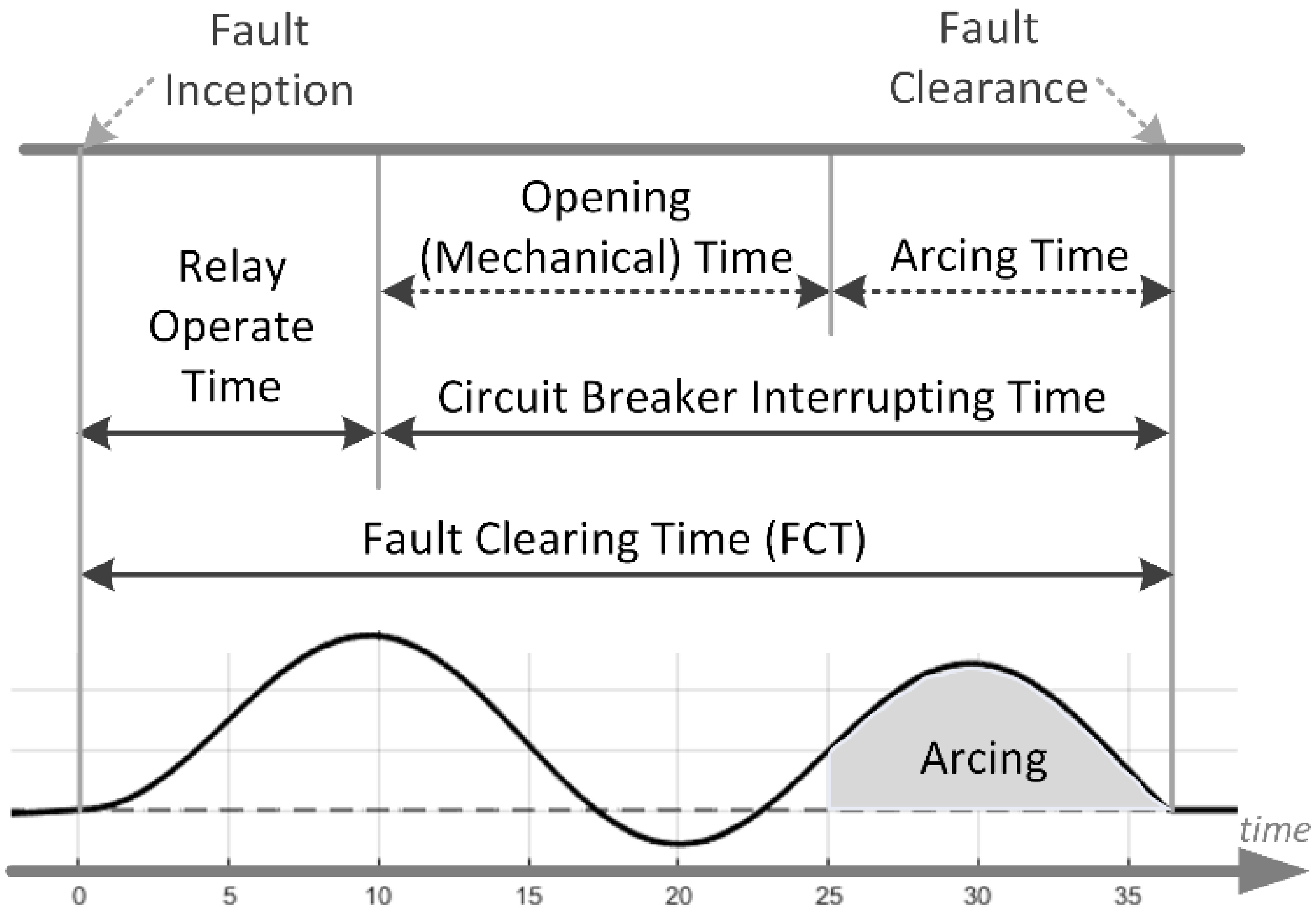
Fault Clearance System (FCS)



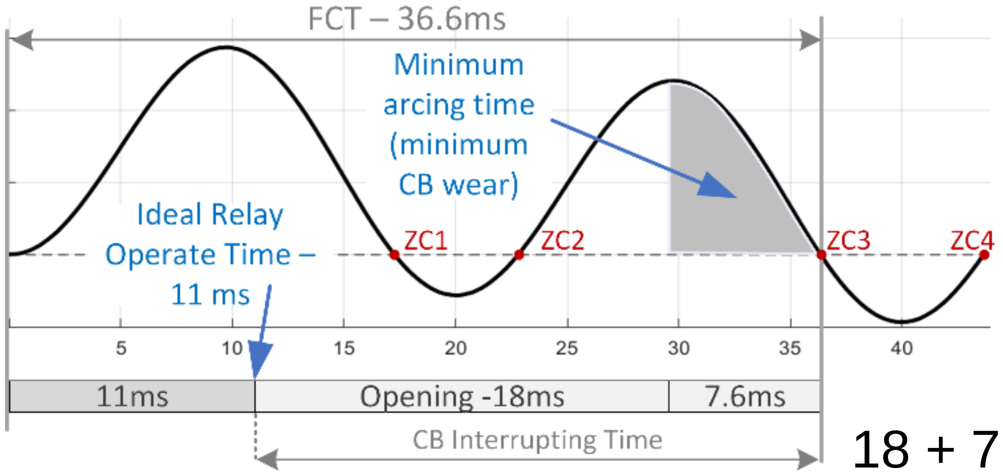
Fault Clearing Time (FCT)



- The arcing time starts when the contacts start to separate
- The current continues to flow during the arcing time
- The arcing time ends when the arc extinguishes, which can only occur at a current zero-crossing
- A minimum arcing time is required prior to interruption of the fault current at the (next) zero-crossing

Relay operate time

- Relay operate time is irrelevant to the power system – the only relevant time is the fault clearing time, i.e. when the fault current is interrupted



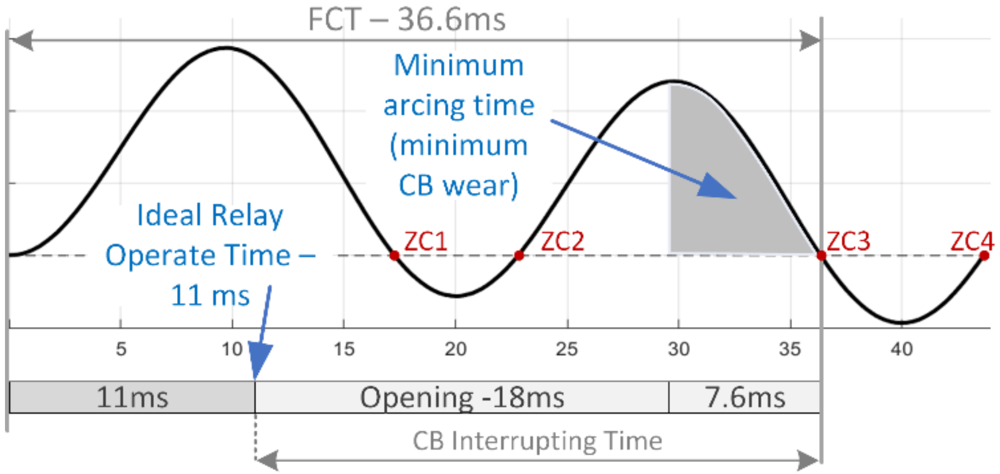
18 + 7.6 = 25.6ms

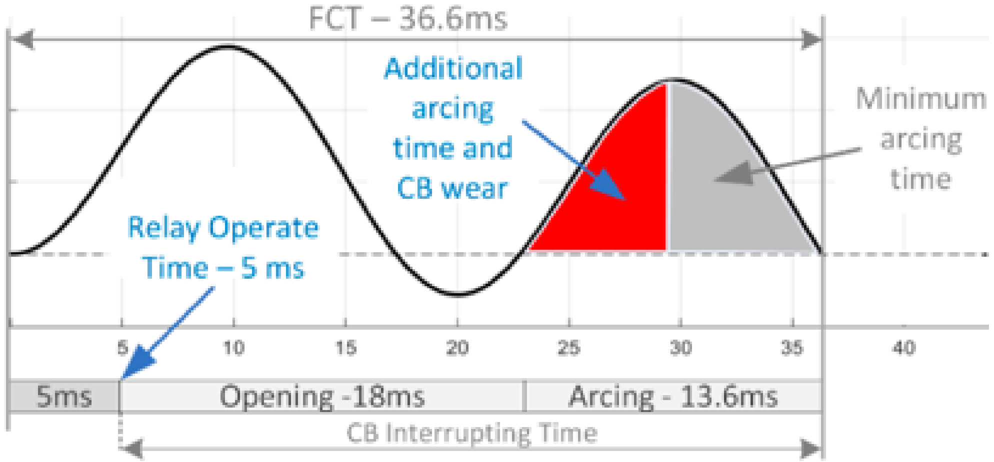
zero-crossing	ZC1	ZC2	ZC3	ZC4
Time [ms]	17.4	22.9	36.6	43.7

- 0-11ms relay operate time → the circuit breaker will interrupt the fault current at the same time

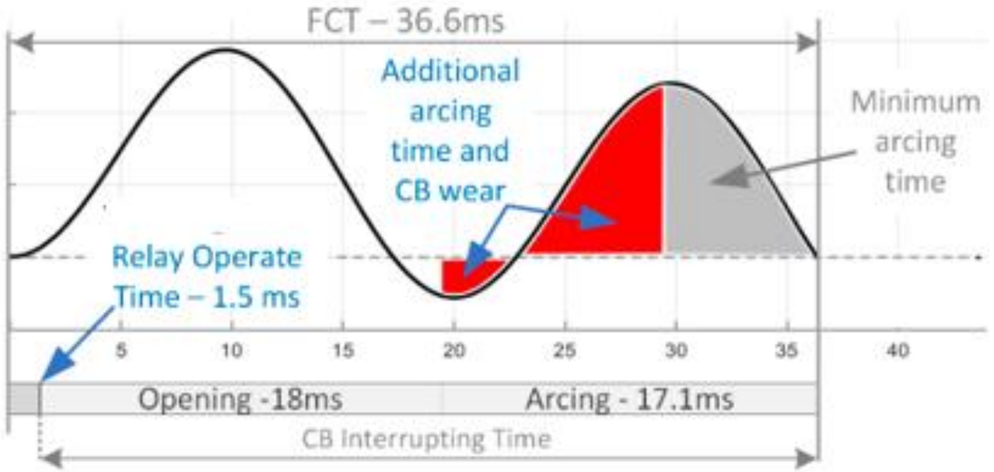
- it's the physical interruption of fault current that's relevant to the power system following the circuit breaker interruption process
- a faster relay operate time does not guarantee a faster fault clearing time, due to the complex physics behind the circuit breaker current interruption process

Relay operate time

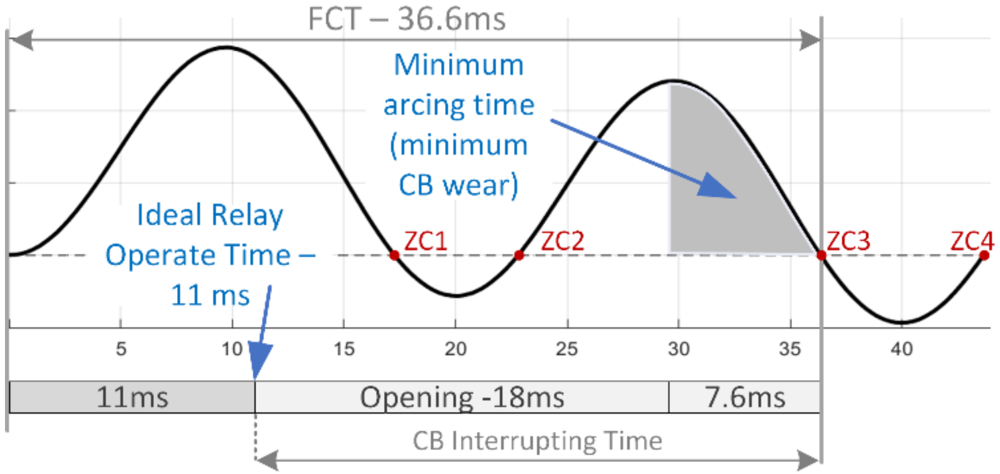




- A faster relay operate time increases the circuit breaker arcing time without improving the fault clearing time

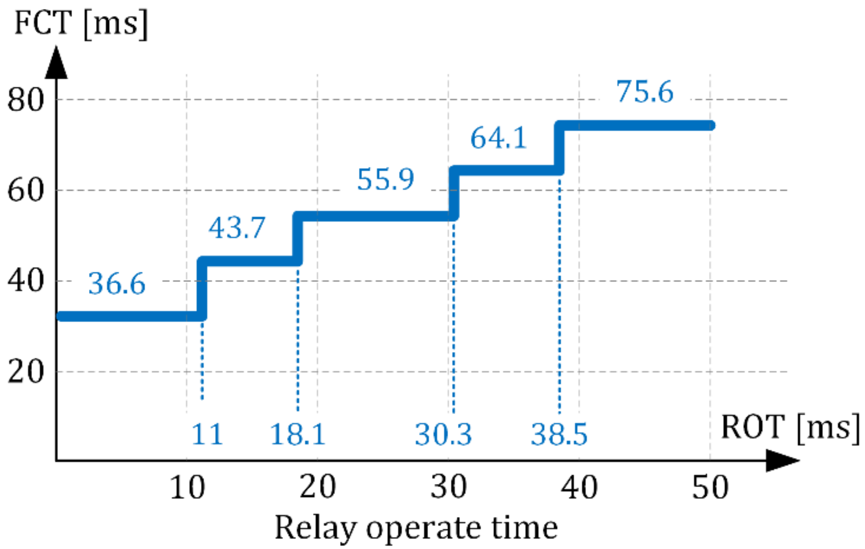


Relay operate time



zero-crossing	ZC1	ZC2	ZC3	ZC4
Time [ms]	17.4	22.9	36.6	43.7

- Relay operate time only matters around several discrete points (e.g. 11ms, 18ms, 30ms)
- At such points an extra ms of relay operate time can make a difference to the FCT – otherwise, from a power system perspective, it makes no difference
- General claims that <u>each</u> ms of reduced relay operate time matters, and directly contributes to power system stability, are misleading



CB international standards

- International standards for circuit breakers (IEEE C37.04-1999 (R2006); IEC 62271-100, Ed. 2.0)
  - state that initiating circuit breaker operation while fault current asymmetry is high is damaging to the circuit breaker
  - recommend relay operate times not shorter than a half-cycle due to the negative affects this has on circuit breaker service lifetime by increasing the amount of cumulative interruption stresses

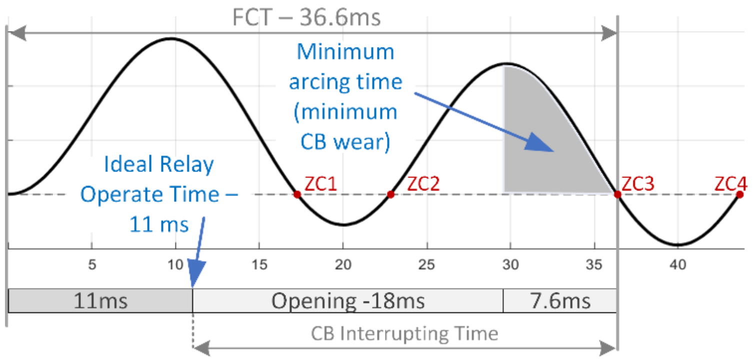
Impact of relay operate time on CB wear

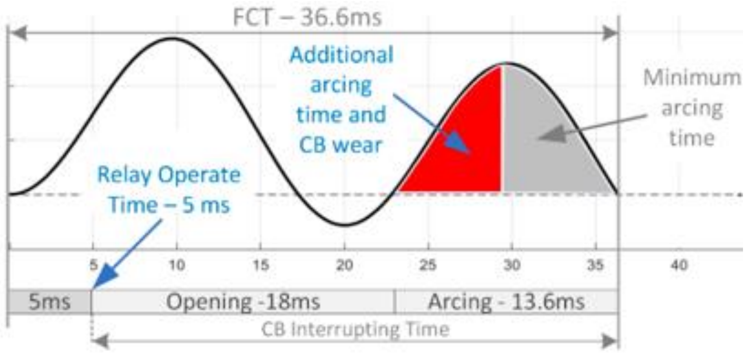
- During the arcing process erosion of the CB contacts occurs – the length of the arcing contacts gradually decreases (which affects the ability of the CB to interrupt the current)
- The most accurate prediction of the amount of mass erosion can be calculated using the following equation

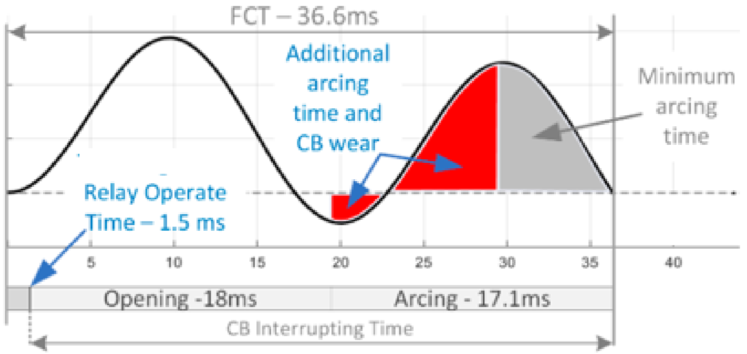
$$\Delta m_c = C \times \int_{\tau_{arc}} |i(t)|\, dt$$

where Δm_c is the mass lost, i is the current, and τ_{arc} is the arcing time

- The integral in the equation is proportional to the area below the current waveform during the arcing time (from when the CB contacts open until the zero-crossing when the fault current is interrupted)

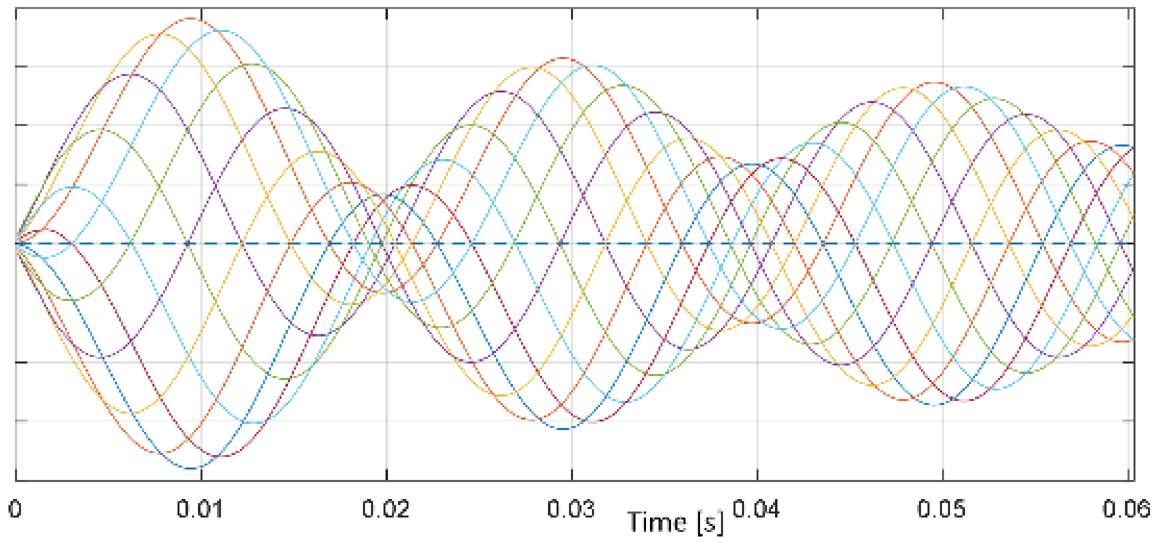






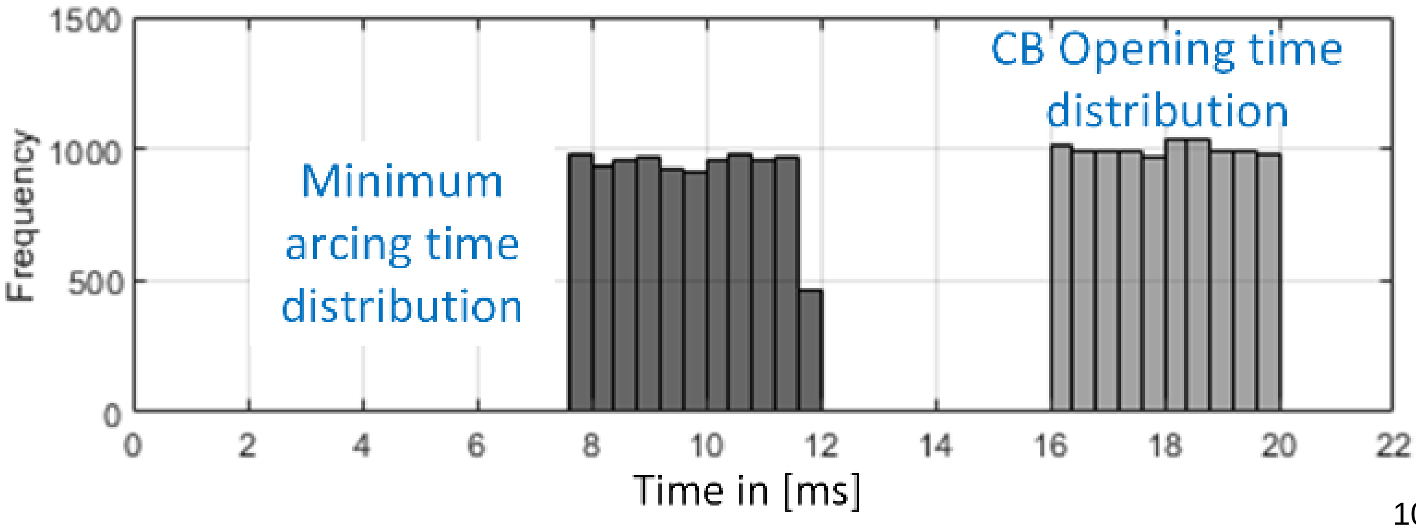
Impact of relay operate time on CB wear

- The impact of the relay operate time on the total fault clearing time and CB wear will differ for different zero-crossings and CB interrupting times
- Analysis
  - waveforms
    - to have a fair evaluation of the impact of the relay operate time on the total fault clearing time and CB wear, generate 12 asymmetrical fault current waveforms having a wide range of fault current asymmetry levels, resulting in different time spreads for the fault current zero-crossings



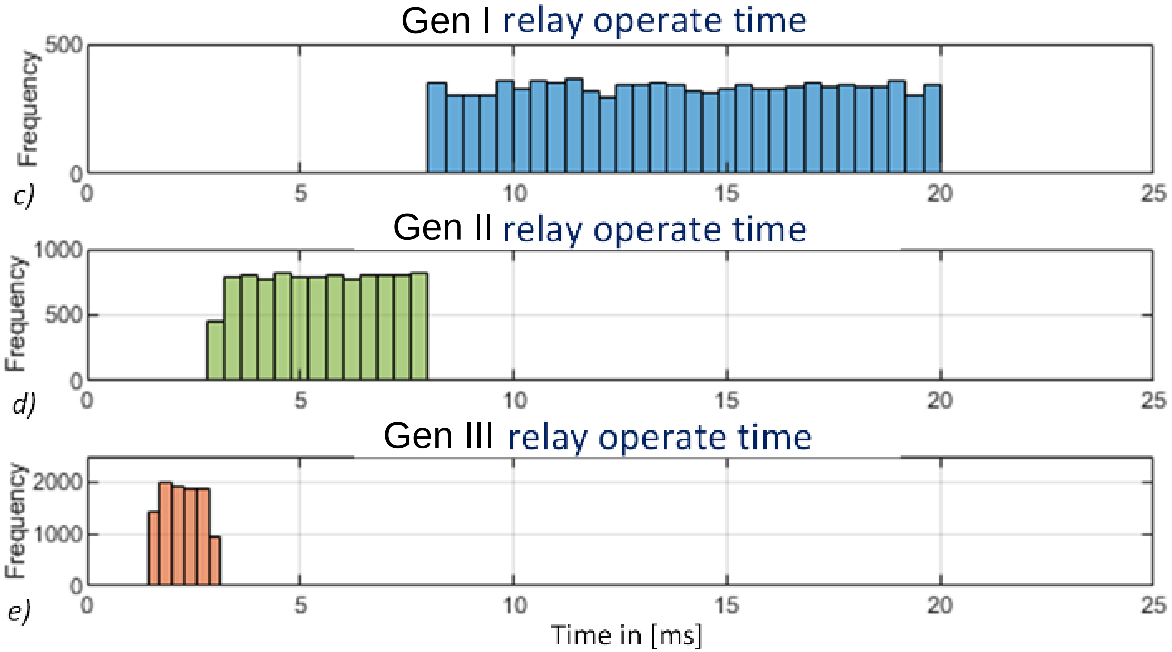
Impact of relay operate time on CB wear

- Analysis
  - CB used: SF6 live-tank (420kV, 63kA)
    - the modeled technical data was based on the type test results performed by an independent and ISO/IEC 17025 accredited laboratory
      - CB operate time = 18±2ms
      - CB minimum required arcing time = 7.6 to 11.8ms
  - generate a table of 10,000 random values assuming a uniform distribution for CB opening time = 18±2ms
  - generate a table of 10,000 random values assuming a uniform distribution for CB minimum required arcing time = 7.6 to 11.8ms



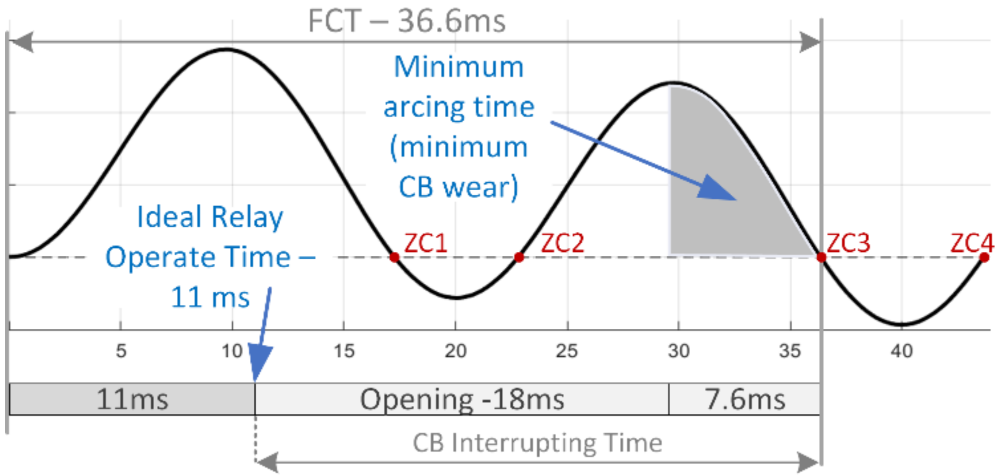
Impact of relay operate time on CB wear

- Analysis
  - relay operate time
    - subdivide into four categories: Gen I, II, III and fixed ½ cycle (= 10ms for 50Hz system)
    - Gen I relay
      - low sampling frequency (<1kHz to a few kHz)
      - operate time 8 to 20ms
    - Gen II relay
      - higher sampling frequency (4 to 10kHz)
      - operate time 3 to 8ms
    - Gen III relay
      - high sampling frequency (≥1MHz)
      - operate time 1.5 to 3ms
  - separately, for Gen I, II and III relays, generate a table of 10,000 random operate time values assuming a uniform distribution



Impact of relay operate time on CB wear

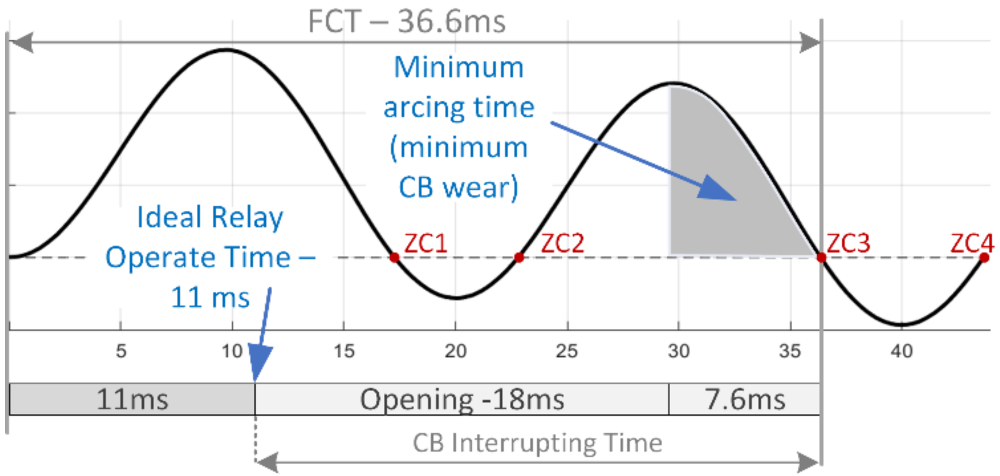
- Ideal relay operate time
  - has an operate time that causes the fastest possible fault clearing time (FCT), and at the same time causes minimum contact erosion of the CB



Zero crossing	ZC1	ZC2	ZC3	ZC4
Time [ms]	17.4	22.9	36.6	43.7

Impact of relay operate time on CB wear

- Ideal relay operate time
  - take waveform 1

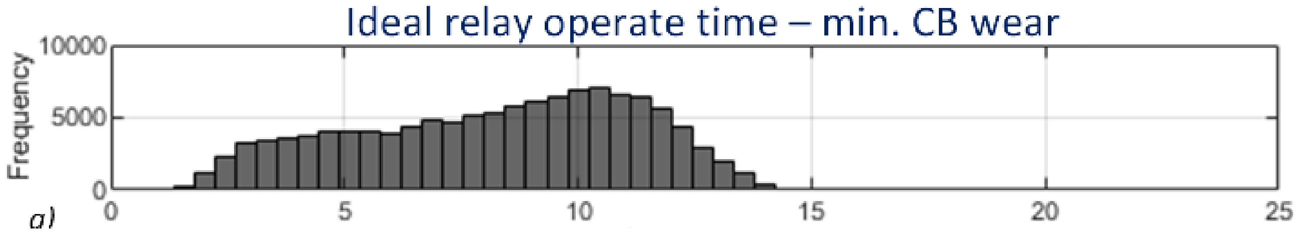


Zero crossing	ZC1	ZC2	ZC3	ZC4
Time [ms]	17.4	22.9	36.6	43.7

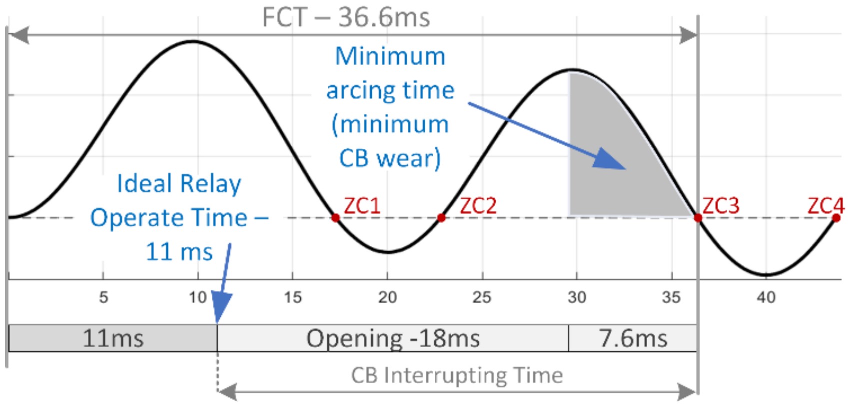
  - take value 1 for CB opening time (18ms) and value 1 for minimum required arcing time (7.6ms) – sum to get value 1 for CB fault interrupting time (25.6ms)
  - find the time for the first zero-crossing > CB fault interrupting time (= FCT for the ideal relay)
  - calculate the ideal relay operate time as the difference between the zero-crossing time and the CB interrupting time (36.6 - 25.6 = 11ms)
  - repeat for CB opening time and minimum required arcing time values 2 to 10,000
- repeat for waveforms 2 to 12 – giving a total of 12 x 10,000 = 120,000 ideal relay operate time values

Impact of relay operate time on CB wear

- Ideal relay operate time

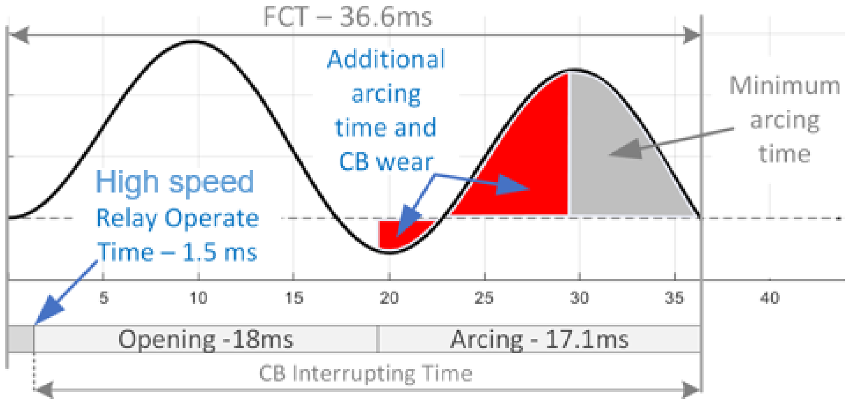


  - the ideal relay operate time results in just the minimum required arcing time prior to CB opening
    - ideal relay operate time + CB interrupting time occurs at a zero-crossing → the CB can open without needing to wait for the next zero-crossing



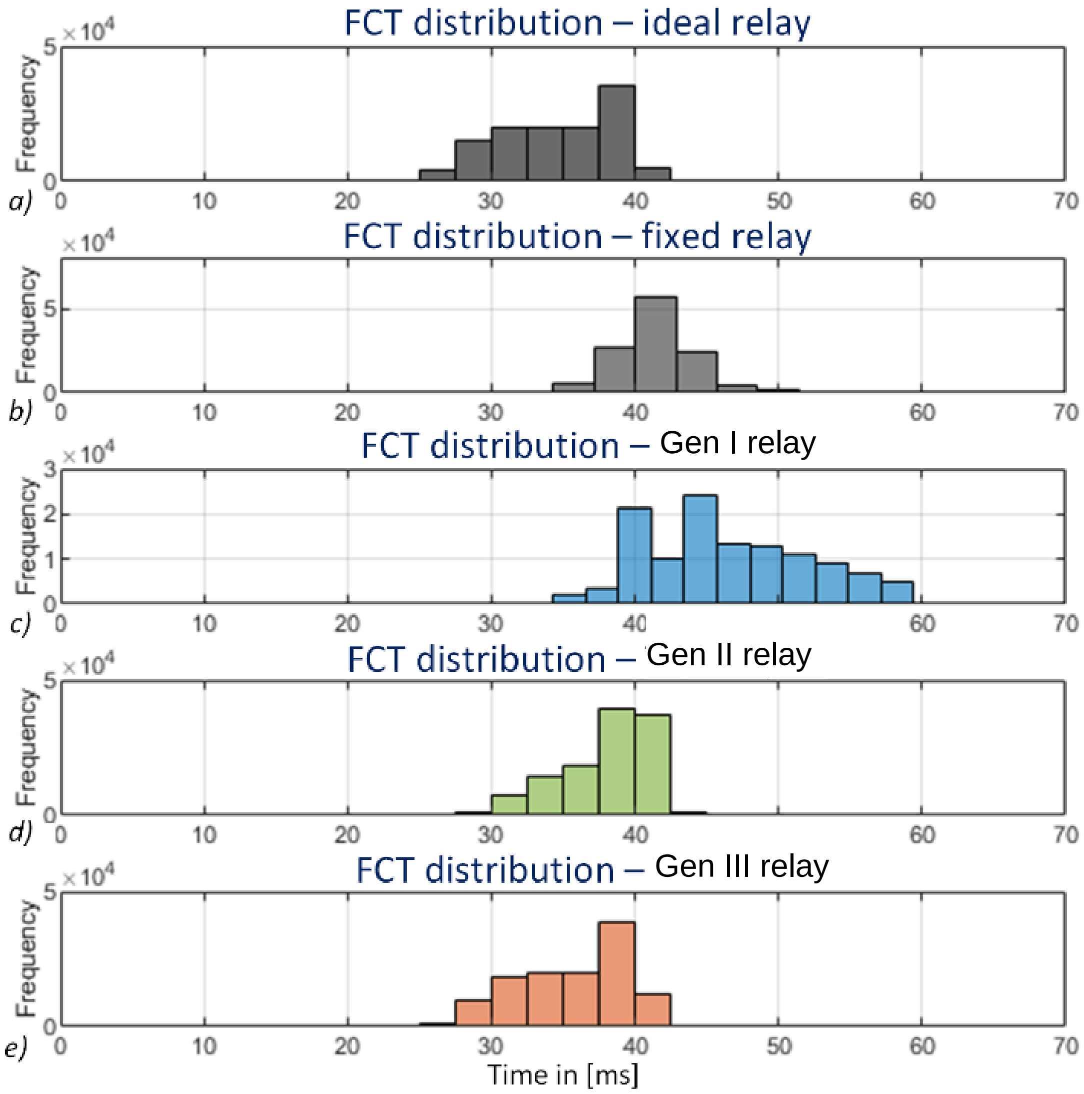
    - there would be no red area

      → so would cause minimum contact erosion of the CB



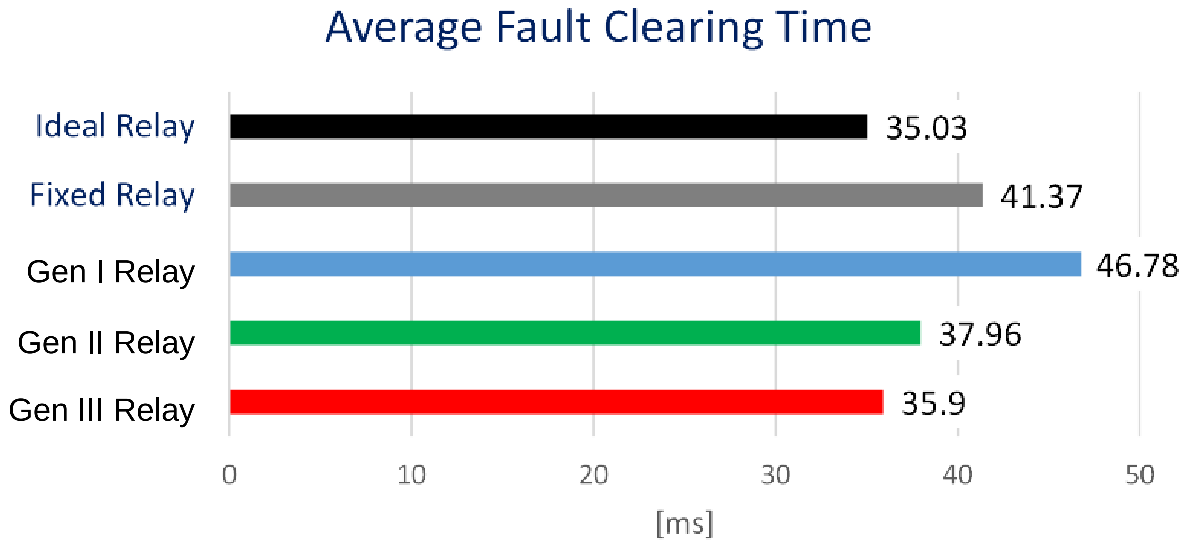
Impact of relay operate time on CB wear

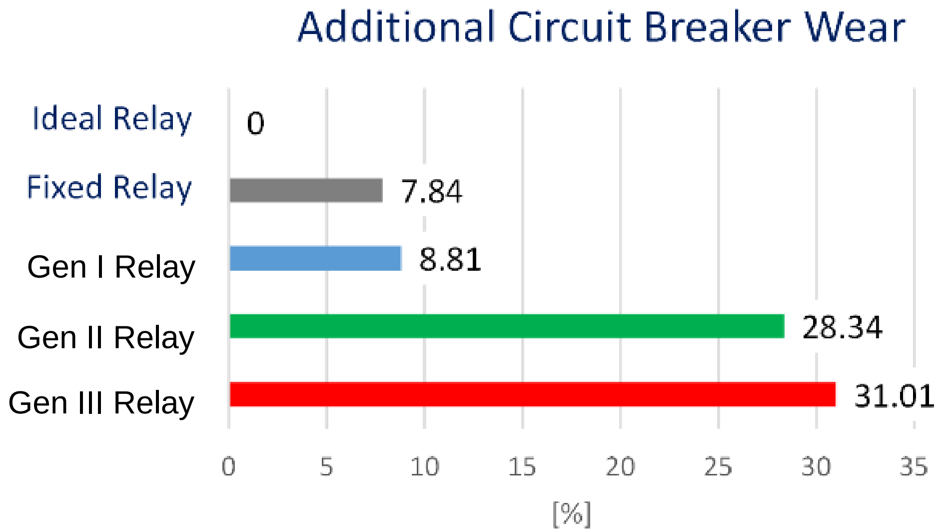
- Fault clearing time (FCT) distribution
  - already have for the ideal relay
  - calculate for the fixed half cycle relay operate time, and for Gen I, Gen II and Gen III relay operate times
    - take waveform 1 and the fixed relay
    - sum value 1 for relay operate time, CB opening time, CB arcing time
    - calculate FCT value 1 as the time of the next zero-crossing > sum
    - repeat for values 2 to 10,000
    - repeat for waveforms 2 to 12
  - repeat whole process for Gen I, Gen II, then Gen III relays



Impact of relay operate time on CB wear

- Results





- even a major reduction in relay operate time brings only a very minor reduction in the real fault clearing time
- the main reason for this is the limitation in the CB technology, which dictates that fault current interruption may only occur at a few discrete instances in time, i.e. at a fault current zero-crossing, subsequent to a required minimum arcing time
- such a minor FCT improvement is paid by an increase in CB wear

Comparison: Fixed relay vs. Gen I, Gen II and Gen III relays

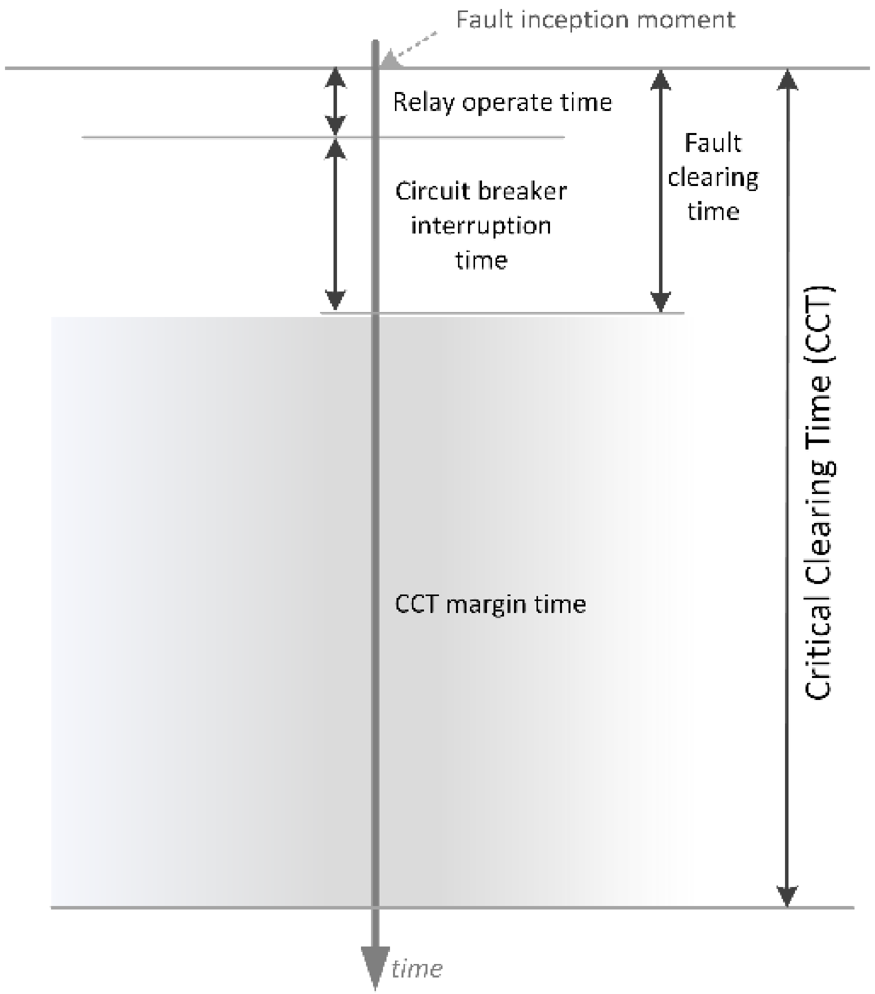
	FCT difference		CB wear difference %
	ms	%	
Gen I relay	+5.41	+13.08	+0.97
Gen II relay	-3.41	-8.24	+20.50
Gen III relay	-5.47	-13.22	+23.17

Impact of relay operate time on power system transient stability

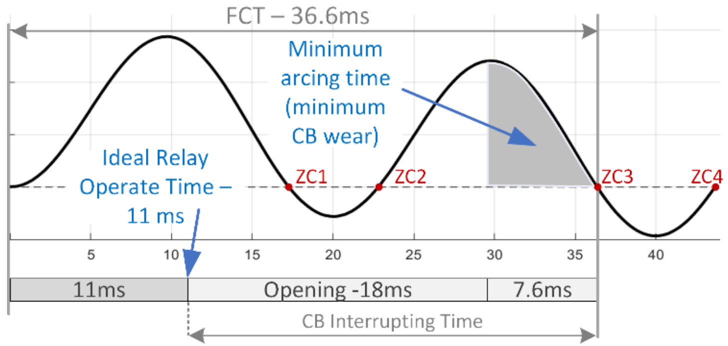
- A common criterion for the evaluation of transient angle stability is the critical clearing time (CCT)
- It is defined as the maximum time during which a disturbance can be applied without the power system losing its stability
  - as an example, in China Southern Grid, the critical clearing time of some 500kV stations is around 350ms
- The main requirement for the fault clearance system is to clear faults faster than the critical clearing time
- There are two scenarios to consider:
  - best-case scenario
    - the closest circuit breaker/s interrupt the fault current
  - worst-case scenario
    - the closest circuit breaker/s fail to interrupt the fault current
    - the breaker failure protection initiates opening of the adjacent circuit breakers, which then interrupt the fault current

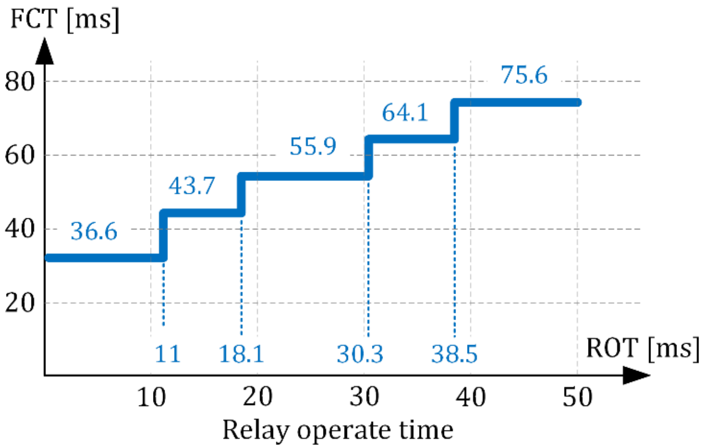
Impact of relay operate time on power system transient stability

- Best-case scenario



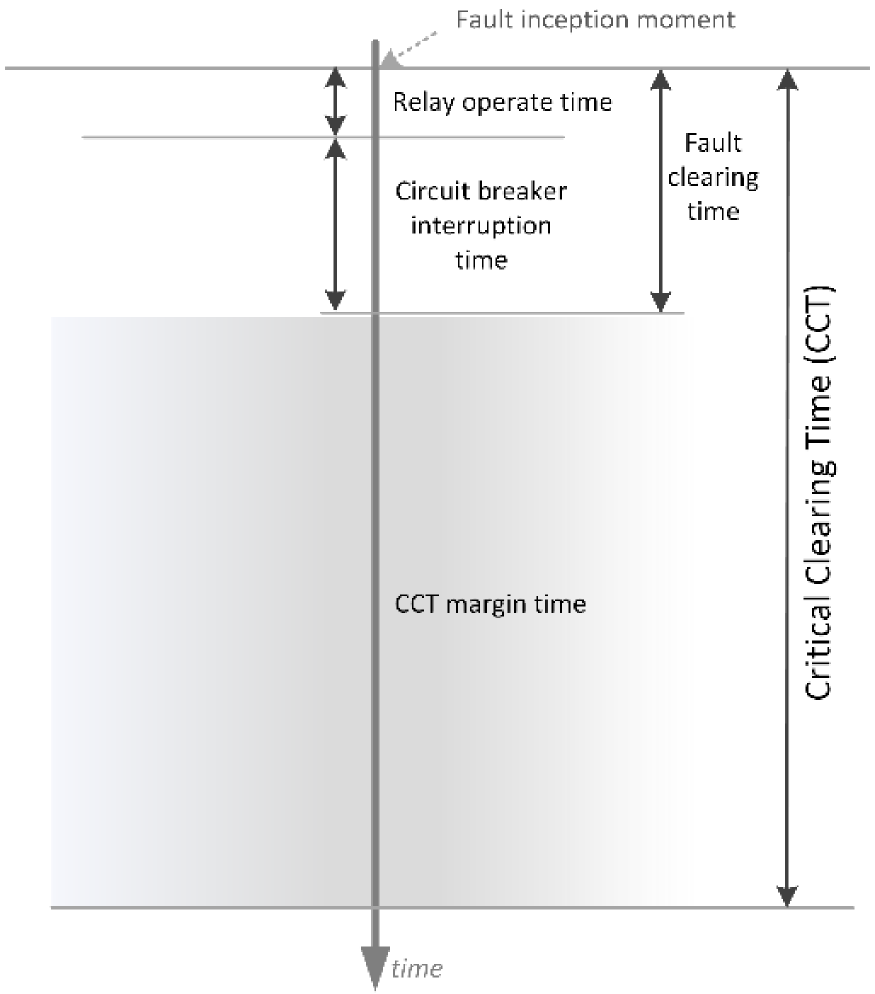
- relay operate time makes an impact on the FCT (and CCT margin time as well) only in a few discrete moments, otherwise it makes no difference



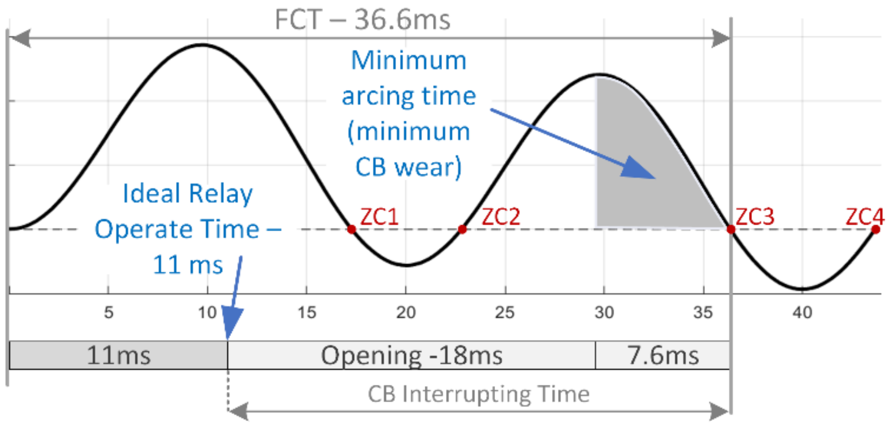


Impact of relay operate time on power system transient stability

- Best-case scenario

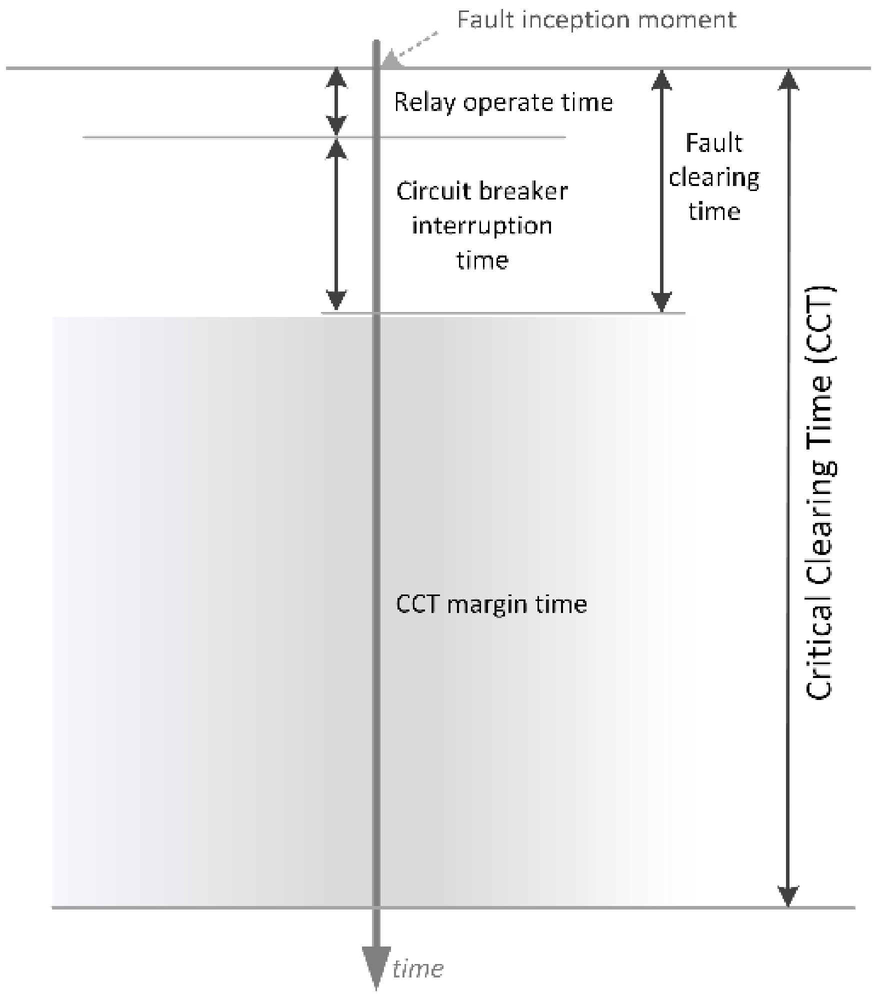


- for comparison, take two relay operating times
  - 1ms, 10ms (< 11ms)
- FCT for both would be the same

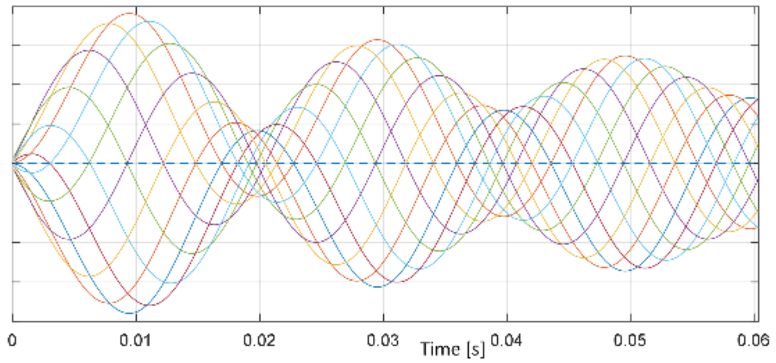


Impact of relay operate time on power system transient stability

- Best-case scenario



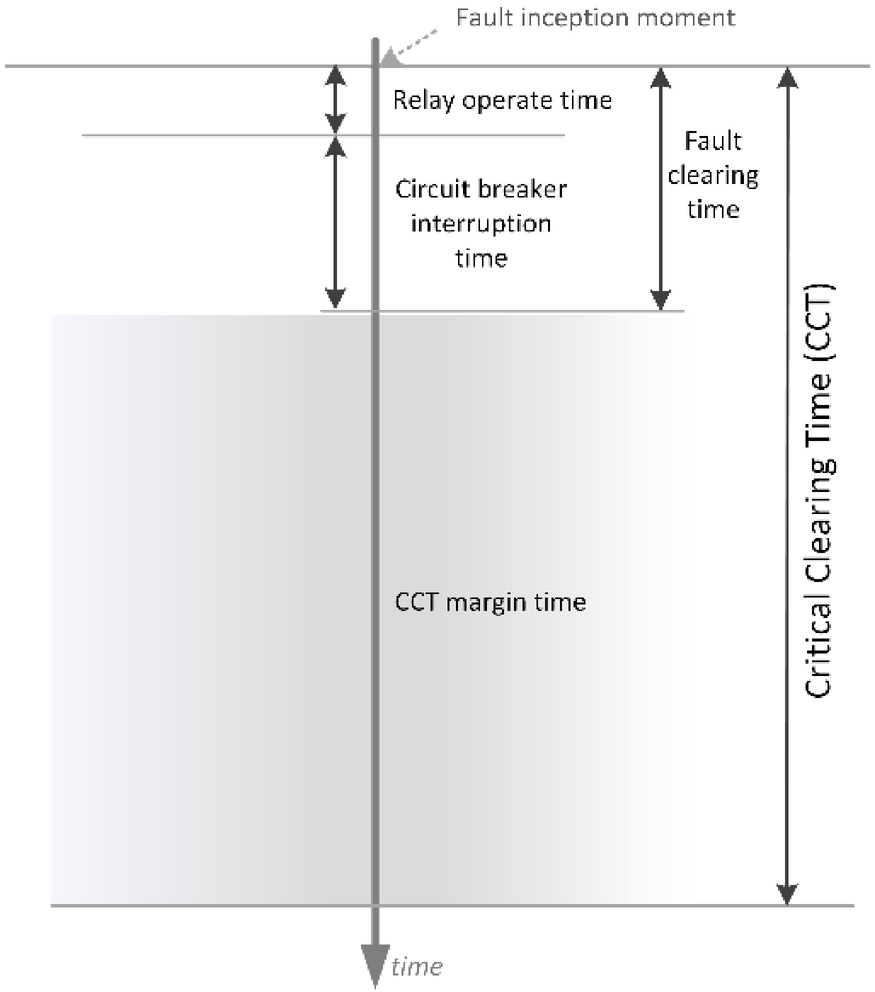
- when considering the other fault waveforms



  - 33% of cases: the 1 and 10ms relay operate times resulted in the same FCT (did not increase the CCT margin time)
  - the other 67% of cases: the 1ms relay operate time did result in a reduced FCT by approximately 10ms (and the CCT margin time was increased)

Impact of relay operate time on power system transient stability

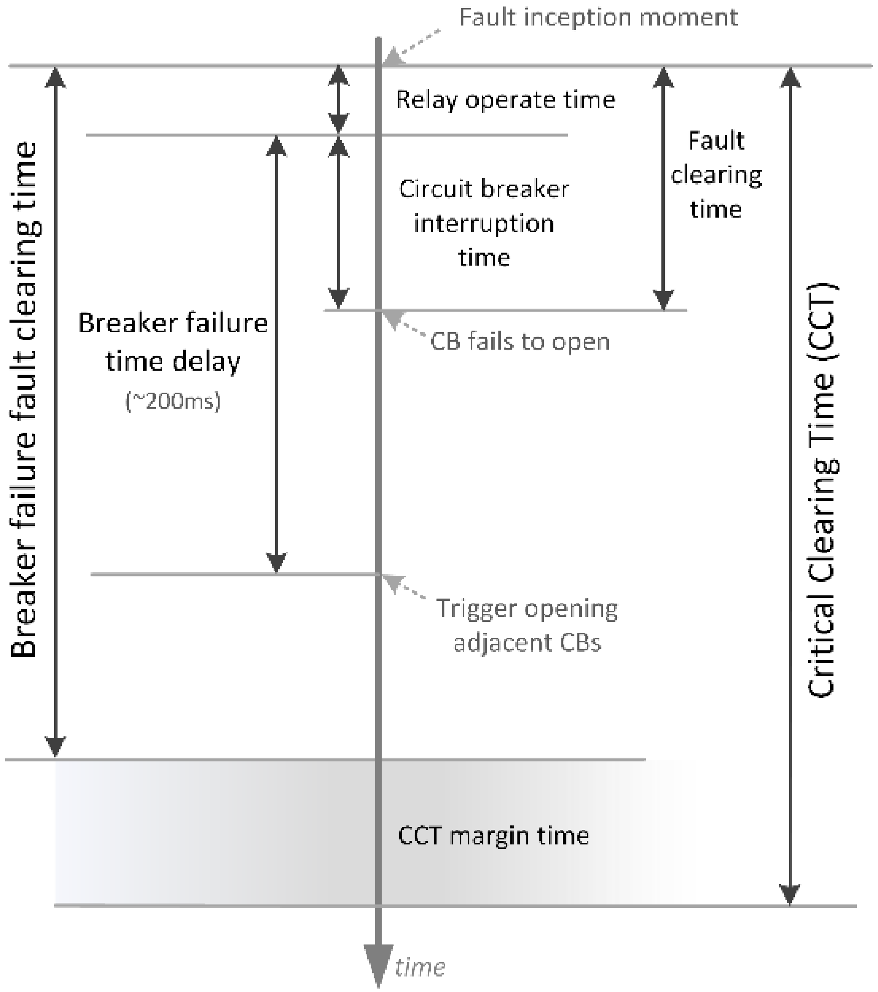
- Best-case scenario



- for a 350ms CCT, a FCT reduction of 50ms to 40ms (giving a 10ms increase in the CCT margin time) represents around a 3.3% increase in the margin time
- 1ms relay operate time vs 10ms
  - does not make any practical difference in the CCT margin time, and
  - does not contribute to the power system stability at all in the situations where the CBs operate as expected

Impact of relay operate time on power system transient stability

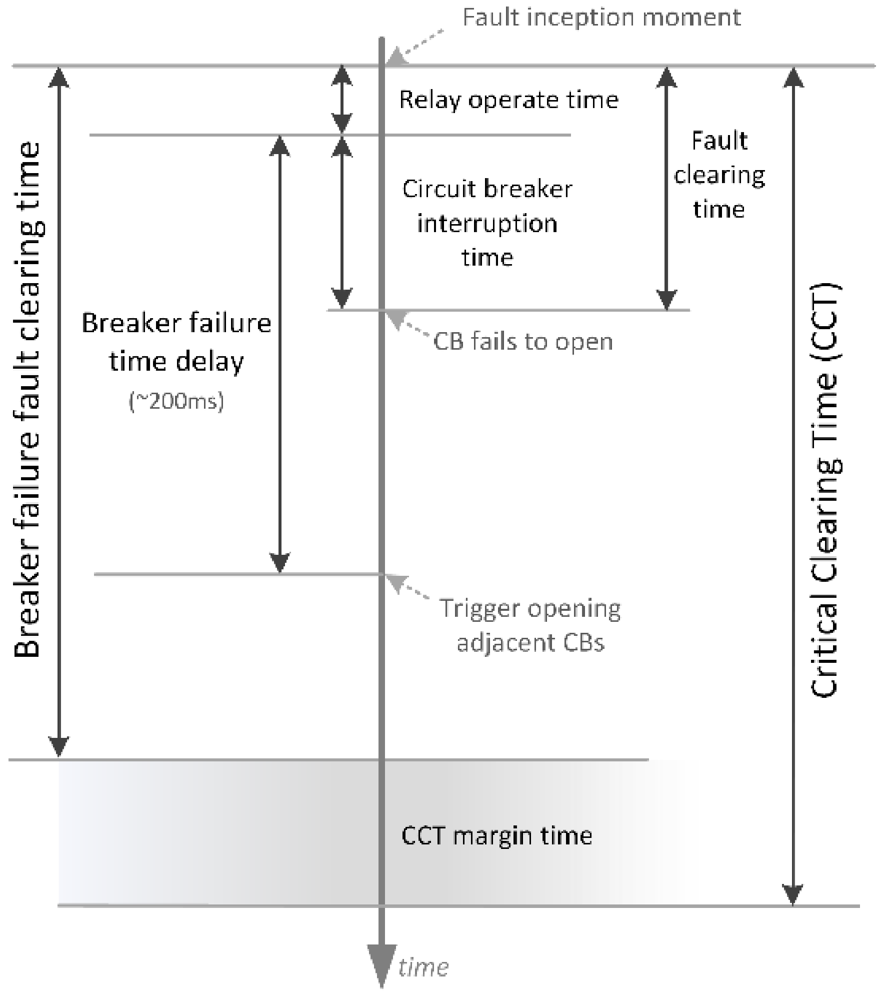
- Worst-case scenario



- the closest CB/s fail to clear the fault and the breaker failure protection scheme initiates opening of the adjacent circuit breakers
- a faster relay operate time would start the breaker failure timing earlier
- breaker failure fault clearing time
  - current interruption must still happen at a zero-crossing
  - current waveforms are now more symmetrical – dc offset decayed – zero-crossings are more equally spaced

Impact of relay operate time on power system transient stability

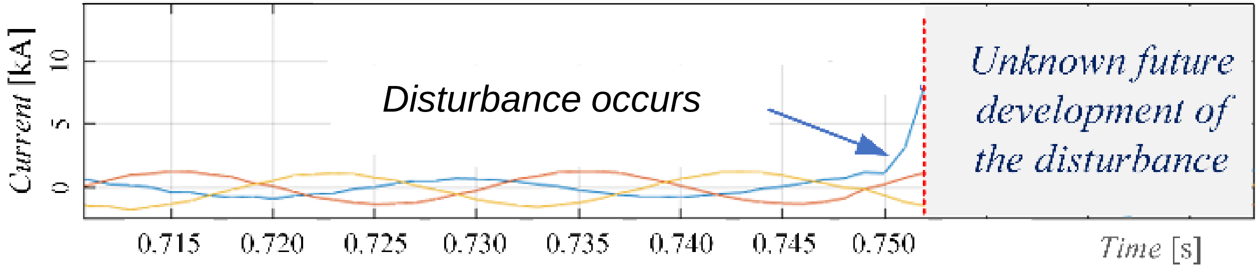
- Worst-case scenario

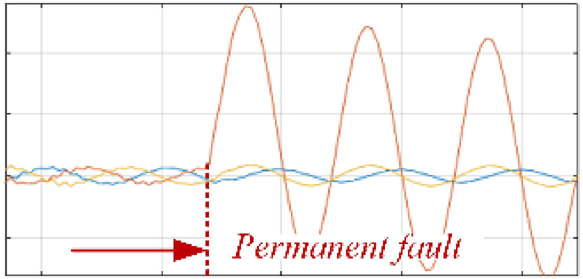


- e.g. 10ms shorter breaker failure fault clearing time (with the same increase in the CCT margin time)
  - for a 350ms CCT, the CCT margin time increases from approximately 30% of CCT to 33% of CCT, i.e. an increase of approximately just 3% of CCT

Impact of relay operate time on protection security

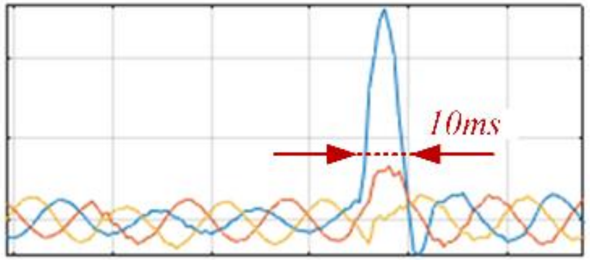
- In most publications in the field of transmission line protection, the shortening of the relay operate time is presented only in a positive context, as helping to maintain the power system stability
- However, ultra-fast relay operation can lead to the opposite effect, where power system stability is affected due to unnecessary relay operation for a non-fault condition
- A protection relay operates securely only if it does not trip the CB for faults outside the protected zone, or for other non-fault disturbances



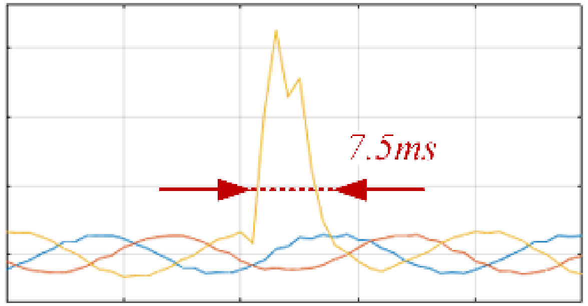


- the disturbance can develop into a permanent fault within the protected zone that requires the relay to operate and trip the CB to interrupt the fault current

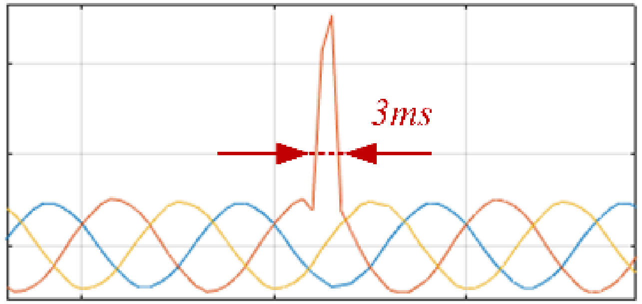
Impact of relay operate time on protection security



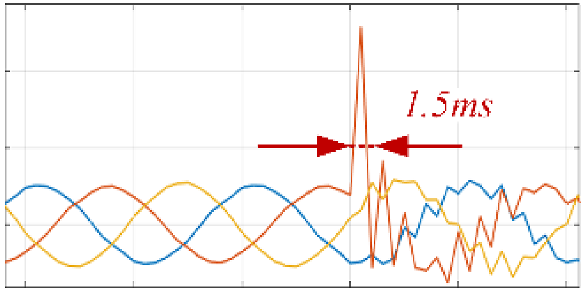
(i)



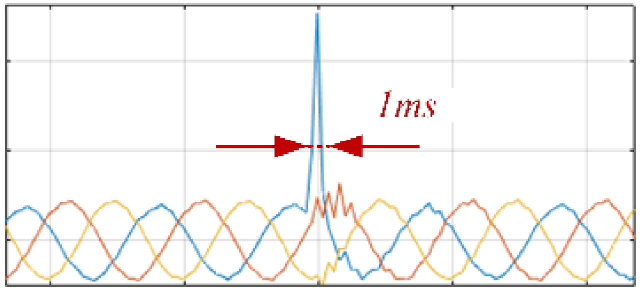
(ii)



(iii)



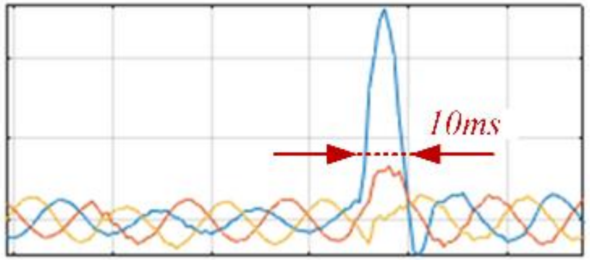
(iv)



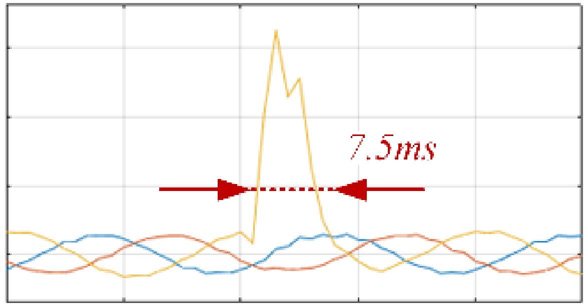
(v)

- The disturbance can also end up being just a short disturbance that does not require tripping of the CB
- Such events occur even on the highest voltage levels, where unnecessary relay operation can be very harmful
  - all recordings shown are for different types of disturbances recorded on 400kV – 765kV overhead transmission lines – a UHV/EHV line must not be disconnected from the system for such occurrences

Impact of relay operate time on protection security



(i)



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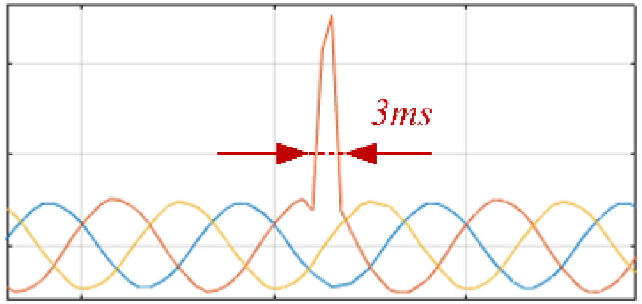

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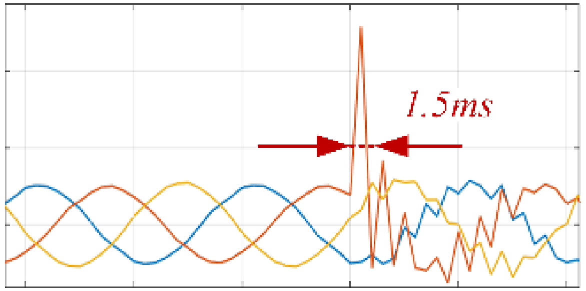

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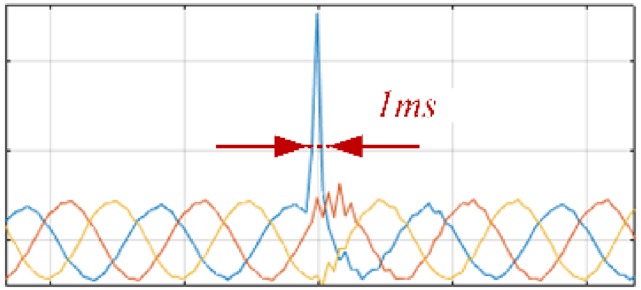

(v)

- Slower algorithms (Gen I relays) would most likely stay secure for all shown disturbances
- Faster algorithms (Gen II relays) could have a problem with longer lasting transients if the decision is made without a bit longer security check
- Ultra-fast algorithms (Gen III relays) might recognize most of the transients as genuine faults if they originate from within the protected zone [detect traveling waves, not faults – all shown disturbances produce traveling waves, but none are real faults]

Conclusions

- In the domain of transmission line protection, a dominant paradigm for many years has been the “need-for-speed” and “faster is better” – it is claimed that each millisecond of reduced relay operate time contributes to maintaining power system stability
- This approach is too simplistic as it ignores the existence of the CBs
  - wrong assumption that the relay operate time, alone, is important, instead of the fault clearing time (which depends on the complex physics of the fault current interruption process in the CBs)
  - the impact of relay operate time on CB lifetime
- Fault clearing time: despite having much faster relay operate times, the Gen III relays bring only a very modest improvement since the potential gain is limited by the existing CB technology
- Circuit breaker lifetime: for only a small improvement in FCT, the faster operate time of the Gen III relays causes significantly higher CB wear
- Protection security: again, for only a small improvement in FCT, the faster operate time of the Gen III relays may introduce a risk of system blackout caused by too short time to distinguish genuine faults from non-fault disturbances